THE MODERN WARSHIP STEAM TO GAS

BY

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AND

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The Background of Change

Sufficient material on naval marine gas turbines has been published over the years to keep the historian well informed; notably the paper delivered by Captain Tatton-Brown in this forum. This article is thus not so much about the prime movers as about the impact on the other elements that have contributed to the style of marine engineering we enjoy today, and the reasons for our change from steam.

At the end of an eventful 1982, it is timely to look back fifteen years to the decisions of 1967. That year was a watershed in the history of naval engineering both for propulsion and for auxiliary systems, of a more abrupt nature than that of sail to steam, coal to oil, or reciprocating steam engines to steam turbines.

By 1967 we had accumulated twenty years' propulsion gas turbine experience from the day MGB2009 went to sea with a 'Gatric' engine. The first fourteen years were all with fast patrol craft until H.M.S. *Ashanti* appeared with her combined steam and G6 gas turbine (COSAG) fit. At the end of this period the reliable G6 turbines in the guided-missile destroyers were beginning to be used on their own as ships companies enjoyed dispensing with the 'base load' steam plant. It meant fewer watchkeepers, faster light up and less steam plant maintenance.

A major lesson becoming apparent during the early life of the G6 gas turbine was that design for *in-situ* maintenance was a handicap. Secondly that, if the Navy was to continue with gas turbines, it would do better to capitalize on the vast running hours accumulated and capital expenditure already lavished on aero engines than continue to design special-to-purpose machines. Thus was borne the concept in 1963 of marinizing a suitable aero engine to replace the G6, and the Olympus TM1A project started. The first shore run of the marinized version came in August 1966.

In early 1965, the Navy had a ship construction programme based on modern steam propelled attack carriers and second generation guided missile destroyers, the latter propelled by a proposed steam/Olympus TM1A COSAG combination. By 1967, this steam-and-gas programme had been virtually destroyed by successive defence reviews until only the first-of-class Type 82 destroyer (H.M.S. *Bristol*) remained, together with a trial Olympus TM1A/ Proteus seagoing ship conversion H.M.S. *Exmouth*. This latter ship's conversion had started as a very far-sighted venture in 1966 and was due for sea trials in June 1968. The interrelationship of these programmes within the general time frame of this article is shown in FIG 1.

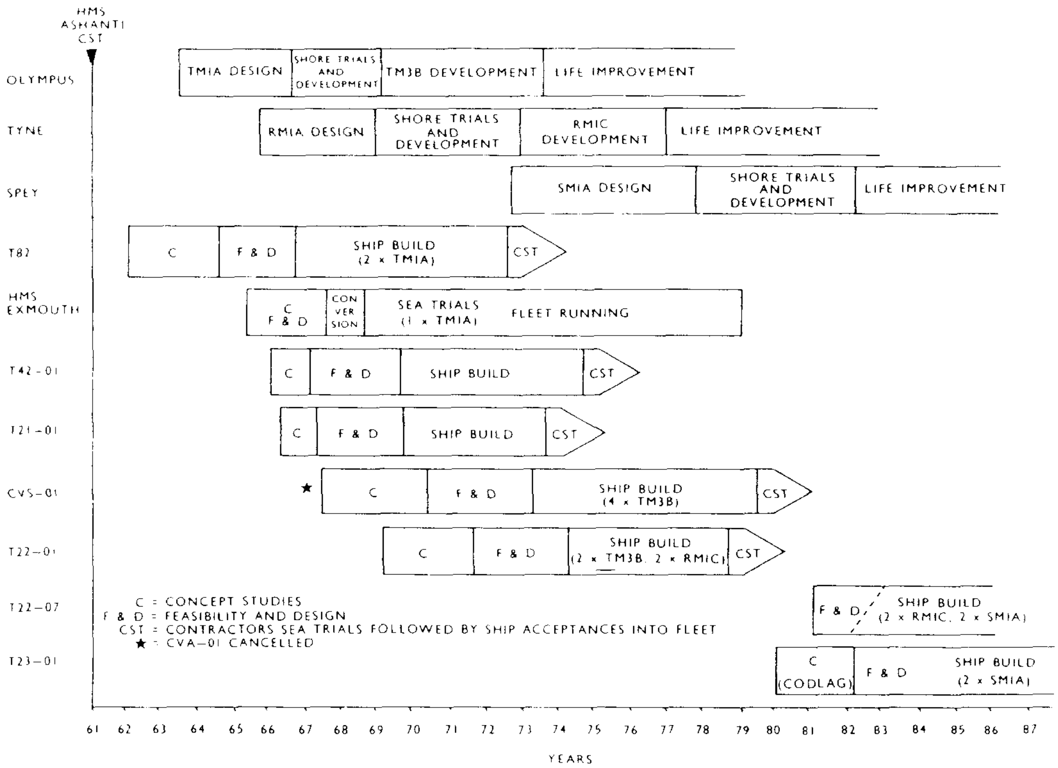


FIG. 1—TIME SCALE OF CHANGE FROM STEAM TO GAS

Those with long memories will remember the loss of the fixed-wing carrier and area air defence and that the times were fraught as now regarding Defence costs and budget constraint. The Navy was faced with the prospect of quickly designing a new generation of destroyers substantially smaller than the Type 82 into which the air defence missile system of that ship had to fit and into which the Type 82 machinery package certainly would not. This was the basis of the Type 42 destroyer.

The mid-60s was also a period of social change in the country, and in the Navy. There was increasing reluctance of people to take up a career which promised grinding and unremitting toil in the service of machinery as demanded by the steam technology of the time. Compared with the great leap forward then being experienced in aero engine and traction diesel technology, steam was in a backwater with a poor image not conducive to recruiting or morale. On the other hand, ships' company's acceptance of gas turbines in the few ships fitted with them was highly encouraging.

The psychological considerations of the time must not be underestimated in the analysis of change from steam to all-gas propulsion. In addition, there were pressing needs to reduce onboard manpower, and to achieve higher availability from the ships themselves. A further consideration was the industrial base on which any surface steam system design and development would have had to rely; it had dwindled in 1967 from a position that was in any case never strong. The disparate manner in the way plant had been procured in the past had ensured a fragmented industry that was not reactive to the swift technological progress required. It also seemed that persisting with surface steam in a very small market (to no seemingly overwhelming military advantage) was flying in the face of fortune—the majority of the marine industry having decided to choose diesel engines, and a buoyant industrial gas turbine generator base was waiting to be exploited.

Although reduction of watchkeeping manpower could have been, and to some extent was, achieved in steam ships by automatic control, there was still left the heavy onboard maintenance load of state-of-the-art steam systems. The desire was not only to reduce this load but move it substantially ashore. Steam systems do not lend themselves to 'exported maintenance' whereas a high technology package of dismantlable modules is ideally suited to refit by replacement. Aero-derived gas turbines with a separate, light, 'hot end' gas generator and a heavier long-life power turbine seemed to offer the prospect both of improving availability and of reducing onboard manpower.

These were thus the points to be considered in 1967. In the background the Royal Canadian Navy had already decided on all gas turbine policy for major escorts with the DDH280 Class (Pratt and Whitney turbines) and the Danish Navy had already a Pratt and Whitney FT4A at sea in combined—diesel—or—gas (CODOG) configuration in the *Peder Scram*.

In this climate, the gas-turbine policy won the day. Had it not done so, many years would have elapsed before a 'window' for such a change would have again presented itself. At the time, it seemed to many that the decision was bold and somewhat out of character with the Navy's general style of cautious evolution. In retrospect, the issues were clear both psychologically and materially, and to have arrived at any other decision at that time for 'traditional' or 'play-safe' reasons would have been not only dishonest but also more risky.

The policy arguments foresaw three gas-turbine power bands being needed:

25-30 000 bhp (18·6-22·4 MW)—to be filled by Olympus

10-15 000 bhp (7·5-11·2 MW)—to be filled by future development

4-5 000 bhp (3-3·2 MW)—to be filled by Tyne

In summary, it is interesting to note that the change from steam and steam/gas combinations to an all-gas main-propulsion policy formally sought to yield the following operational, technical, industrial, and social advantages:

(*a*) Greater availability of the ship by:
  - (*i*) shorter and less frequent refits;
  - (*ii*) reduced onboard maintenance;
  - (*iii*) high reliability.

(*b*) High maximum speeds coupled with high deployment speeds over long distances.

(*c*) Improved endurance overall.

(*d*) Ability to get underway quickly to full power.

(*e*) Smaller complements.

The health (or otherwise) of the industrial base and the psychological factors in the change regarding morale, recruiting, retention were not stated but clearly influenced the decision.

Some wise counsels in industry in the later 60s were apprehensive that the chances of achieving all these laudable aims with gas turbines alone were slim. The problems of salt attack, both air and fuel borne, low overhaul life, adverse fuel consumption, large ducting, ship stability problems, the high-quality fuel required, funnel gas temperature and noise, complications with propeller reversal, and complicated auxiliary energy considerations were only some of the points brought up. There were strong arguments in favour of diesel propulsion engines, particularly for the cruise conditions. Political constraints on the physical size of the Type 42 destroyer design precluded their adoption for that class since the then currently available U.K. engine's volume to power ratios were over twice that of marinized gas turbines.

Implementing Change

From the outset, it was clear that success would only come with gas turbines as the sole prime mover if success also attended the engineering of all the peripheral systems, large and small.

However, time was not on our side. There was no time to construct a full-scale shore test plant of the proposed package. In retrospect, it can be clearly seen that success or otherwise has attended our efforts with the peripheral systems in direct proportion to the excellence, or otherwise, of their detailed engineering implementation at that time, in terms of excellence of the original specification, the detailed design and the subsequent production and installation. Although shortfalls have been few, some of them have had an adverse impact totally out of proportion to the excellence of the execution of general policy. The truth is that our design solutions had limited margins. The demands of timescale, political constraint, and innovation during the period 1967–74 produced a salutary epoch where the professionalism of all concerned was well tested. Where we failed to live up to our ambitions we gave ourselves a deal of hard work and expense. Some of the problems are still with us. Do not forget however that our standards are very high and when faced with the ultimate test of war the equipment performed. There were no operational embarrassments in the recent South Atlantic conflict.

Some of the problems have come from early solutions that were over-engineered or over-complicated. Others from a lack of appreciation of the need for quick diagnosis of faults, or the effect that unreliable auxiliary machines and systems could have on total mission availability. The unreliabilities have usually been in equipments and systems that in the days of steam were not as vital as they have become in a gas-turbine Navy. Diesel generators, high-pressure air compressors, and auxiliary boilers are in this category. They were not accorded as high a priority for development resources as where the gas turbines themselves, and this will be commented on later. In contrast, some equipments of fundamental significance to steam plant which were carried on into the gas-turbine age, like steam-driven flash evaporators, have performed excellently by any standard.

Implementation of the all-gas-turbine policy followed three practical routes. Firstly, the *Exmouth* trial of Olympus TM1A/Proteus combination, already being prepared when the policy was formulated, resulted in a most valuable period of six years running at sea from June 1968 until the trials mantle was taken over by H.M.S. *Amazon* in 1974. Concentrating mainly on Olympus installation testing, *Exmouth* showed the importance of getting the intake and uptake configuration right (a wrong first shot caused the first Olympus failure after only 64 hours) and the need for very careful design of sea spray eliminators. By February 1973, the fourth gas generator change Olympus had run 3000 hours at sea, fully justifying the confidence placed on its eventual success.

One of the achievements of H.M.S. *Exmouth* was in essence psychological, exemplified by a contemporary verbatim comment by one of the ship's engineer officers later on in her life, after *Amazon* had gone to sea:

> 'It ought to be repeated that the greatest single factor in the various successes enjoyed by this ship has been the response of the men who have sailed in her . . . there is considerable job satisfaction derived from operating a gas-turbine propulsion system, and it is with great pleasure that we heard MEOs of other COGOG ships emphasize the favourable reaction in their departments to all aspects of their work . . .' (*J.N.E.,* Vol. 23, p 205, 1976).

The two other implementation routes were through the lead design Type 21 frigate H.M.S. *Amazon* at Vosper Thornycroft, and the lead design Type 42 destroyer H.M.S. *Sheffield* at Vickers. Although hull, weapons, and auxiliary machinery were different, the main propulsion package and ancillaries were essentially the same, both based on the Ministry/YARD design COGOG solution of 20·8 megawatt Olympus TM3B, 3 megawatt Tyne RM1A, SMM controllable-pitch propeller, and HSDE electronic analogue machinery control. Also common, by Ministry direction, was the Paxman Ventura diesel generator, the DBI gearbox, and standards for fluid systems pipes and valves. Apart from the Olympus derivative, all these were different from *Exmouth.*

The two projects were to the same timescale with H.M.S. *Sheffield* intended to be the first demonstrator, but it was H.M.S. *Amazon* that went to sea first on the 20 July 1973, heralding the new age. She was not without trouble and a great deal of seagoing development work ensued until her acceptance on 4 May 1974. Much of this was read across to the delayed H.M.S. *Sheffield,* enabling her to start sea trials on 30 June 1974 with much greater confidence and success. Their speedy conclusion after only 27 days at sea gives testimony to the efficacy of the solutions evolved at that time.

Since then, the practice has been one of steady evolution and eradication of technical difficulties together with development of the marine Spey (SM1A) to fill the intermediate power range gap. It is pleasing to note that there has never been any difficulty in gaining the acceptance and enthusiasm of commanding officers and ship's companies for the style of propulsion systems accorded them, amply justifying one of the original 1967 underlying aims of improved morale.

To illustrate this article's theme of impact on other elements of the package caused by gas turbine introduction, the following vital technical areas have been chosen for deeper analysis.

Transmission Considerations—Reversing

The detractors of gas-turbine propulsion have always pointed to the problems associated with the uni-directional rotation of the prime mover, and how much simpler it all is with steam. There are really only two practical alternatives a reversing gearbox (RGB) or a controllable-pitch propeller (CPP) and the R.N. has tried them both. In terms of ahead propulsion efficiency the RGB shows a slight advantage and, where gearbox space is limited, the only other option is CPP. Similarly, where quick response and high astern powers may be required, CPP is again to be preferred. On propeller noise, there is not a lot in it provided the CPP propeller is running near design pitch. Characteristically the CPP brings complexity and the greater need to dock should things go wrong.

By the end of the sixties, the Navy had twenty-five reversing gearboxes at sea in the two combined-steam-and-gas plant classes—TRIBAL Class frigates and COUNTY Class destroyers. As with propulsion plant, the boxes were similar, from the same manufacturer, and with some common parts. Later experience with them, considering their complexity and innovation, has been extremely good. The boxes continue in service to this day. The hydraulic couplings and the associated self-shifting synchronizing (SSS) clutches for engaging the reverse gear train have proved particularly successful. It was not such a happy story during the early part of their life however, and a prejudice against them remained in some quarters when the Type 42 choice was being made.

The primary force pushing the R.N. away from this well-tried RGB solution to something completely new was, however, space. With the technology of the time, it was simply not possible to fit a gearbox with the required reversing power into either the *Exmouth, Amazon,* or *Sheffield* hulls. In *Exmouth's* case, it was also much cheaper and quicker to fit a commercial KaMeWa design single-acting CPP unit using an 'open-circuit' hydraulic system with fixed displacement pumps. In the case of the *Sheffield* Class, the political constraints mentioned earlier precluded all attempts to secure the larger hull that was needed at the time. Only recently have we been able to build a Type 42 hull 0·6 metres wider and 15·4 metres longer. This would have accommodated an RGB solution.

The immediate success of the *Exmouth* transmission system (albeit with a myriad of minor snags) gave us a false optimism. With that ship, there were virtues of rugged simplicity and well-tried commercial practice. For reasons that are now suspect these were not carried forward into the new classes. The forces leading us to build in problems with our current CPP systems stemmed in the late '60s from two sources—the Ministry, and the Industry.

Firstly, the Ministry. In H.M.S. *Exmouth* (at 13·9 MW per shaft), the CPP system was built under licence by Stone Manganese Marine (now Stone Vickers). Stones surrendered their licence at the end of 1968, and the system since employed in all our frigates and destroyers driven by gas turbines has been to the Stones in-house XX design. This is a double-acting type with closed-circuit hydraulics and variable displacement swashplate pump. This style of actuator and hydraulic system is unique to the R.N. and was imposed on Stones by the Ministry, seemingly against the contractors wishes and recommendations. The contractors fears were well founded for the system has given us problems and expense, and the reasons for its adoption are worth analysing.

The double-acting design of hub was chosen because, in response to the Ministry specification for unlimited pitch changeability at full rev/min, very high blade spindle torques were predicted by the Admiralty laboratories. Not only did these predicted torques suggest a double-acting design (to even up the trunnion thrusts) but also the actuating oil pressures were predicted to be much higher (at 1200 psi) than current practice. Because Stones did not have experience of hydraulic systems at this pressure, it was decided to engage an aircraft hydraulics firm (Dowty) who did have expertise and who were already under contract to the Ministry in developing a NEL design swashplate high performance pump for other purposes. The high-pressure requirement thus led to a sophisticated non-commercial NEL style (Downel) pump.

Compared with an open-circuit design the hydrostatic type of operation offered some theoretical simplification. The avoidance of the servo-valve/constant-displacement pump combination was one attraction. The ready provision of the high oil-flow rate required by the specified fast pitch reversal was another. With pump output matching demand at any instant, the churning losses should be low and oil coolers unnecessary. Oil filters between pump and shaft could be discarded. On clean oil Dowtys (the pump supplier) were confident of reliability. The Downel pump was selected.

Secondly, the Industry. Design and development proceeded at headlong pace during 1968 with five different contributors acting in a less than satisfactorily co-ordinated fashion until in 1969 the design sponsor woke to the dangers and looked for a number of changes. But it was too late. The system could not be changed if the programme was to be kept. Later on it was found that, in fact, the churning horsepower dissipated into heat by the Downel pump was much higher than at first assumed, and an oil cooler was essential. This negated one of the original arguments for the hydrostatic system—but again too late.

Service Experience

In the event, the pump turned out to be exceptionally sensitive to oil contamination, difficult to repair, and the pipework difficult to flush after contamination. Without a constant full flow in service, it was not possible to keep the oil clean. Had there been room, full-flow barrier filters each side of the swashplate pump could have been introduced but the solution adopted was to open up the pump clearances and accept even higher churning losses. This has been successful.

One of the bitterest pills was served up during *Amazon*'s sea trials when it was found that, for the manoeuvring mode adopted, the propeller blade spindle torques experienced were only a quarter of those predicted with hydraulic pressures hardly rising to 300 psi. We now know in fact that single-acting CPP hubs work perfectly satisfactorily up to 28 MW per shaft, this being the figure currently produced by a KaMeWa derivative design now fitted to USN FFG 7 and DD963 class ships. It was also found during those sea trials that the ahead-to-astern blade pitch change rate designed to meet the staff requirement was two times faster than either hydrodynamically necessary or mechanically prudent in respect of gearing stresses. In increasing the time from 15 seconds to 30 seconds, the need for such a high output pumping device was also removed.

Much as we would have liked to do so, it was far too late to change the system for the Type 42 after the *Amazon* trials. It resulted in a maze of pipework some 568 metres long, containing 900 separate pipes and 166 valves, initially requiring 22 flushing loops to get it anywhere near clean. Shipbuilders found it difficult to install and set to work. In one particular instance (H.M.S. *Newcastle*) the whole of one system had to be dismantled piece by piece to effect cleaning after contamination. It took four weeks. The hydaulic hygiene demands constant awareness and vigilance by our shipbuilders and crews, but where care is exercised very little system trouble now results. Maintaining these high standards is, however, in the category of self-inflicted injury, for had we made more realistic estimates of torques and actuating times we would probably have fitted a low-pressure constant-flow single-acting device, as offered originally by the two Stones competitors KaMeWa and LIPS (already chosen for the Canadian DDH280 Class), and obviously could have been produced by Stones if need be.

Partly because we had embarked on a firm policy of identicality and configuration control between shipbuilders building follow-on ships of the Type 42 Class, ostensibly to make them cheaper to build and easier to support through life and partly because there was no time for re-design, the original CPP system was repeated for the first six ships (Batch 1). However, the Ministry did commission the lead shipbuilders (Vickers) to design a simplified pipe system to the new parameters. Again, owing to the lack of time or funds to carry out the radical re-design needed, this was a somewhat superficial exercise, but has resulted in a much more acceptable closed-circuit system. It incorporates most of the 64 official modifications to the early design to make it more reliable, easier to build, and to flush.

It is pertinent that the Type 22 frigates, of which so much was made in the recent South Atlantic operation, had their sketch design frozen in 1972, before either *Amazon* (July 73) or *Sheffield* (June 74) went to sea and the main propulsion system was to be identical. A rigorous reliability assessment at the time showed that neither the modified original design nor the Vickers simplified design were theoretically as reliable as the open-circuit screw-pump-driven system being pressed for by Stones for the new class. However, it must be remembered that at that time we still did not know that we had designed to the wrong parameters. Accordingly, and despite Stone's earnest entreaties, we continued with the closed-circuit design and put a lot of effort into ensuring that the pipe lines were neater and easier to flush.

As more ships joined the Fleet the issues became clearer and, finally, the Ministry commissioned in 1977 an open-circuit design similar to that originally discarded in 1969. All the ideas and experience of the shipbuilders, the Ministry, and the manufacturer were taken into account. After five years of design and development trials, we now have an open-circuit system being built into the sixth Type 22 and the thirteenth Type 42. It has considerably more than halved the length of pipework and the number of valves, and tolerates lower standards of hydraulic hygiene. We await the sea trials in 1983 with great interest.

Mechanical Aspects of the CPP

The hydraulics of the CPP system has not been the only problem. In H.M.S. *Exmouth,* minor trouble had been experienced with the 'zero thrust' position of the CPP blades 'floating' due to expansion of the feedback rods of the shafting to the position transducer on the gearbox. The need to feed hot air (from the gas turbine compressor) down the shaft for propeller silencing in later classes enlarged the problem. Thus was designed the current inner and outer concentric oil-transfer (OT) tubes, the outer being fixed to the propeller hub and the inner to the blade turning gear. These tubes are brought out through the gearbox to a main shaft extension oil-transfer box. On this box is the movement transducer pick-up, the transducer case being mounted on the outer tube and the pick-up taken from the inner. On the assumption that in the nested tube arrangement the oil temperatures are similar, the design neatly compensates for expansion. To make doubly sure, the tubes and couplings were made of a low expansion coefficient steel alloy (NILO). To ensure that the hub was not subject to sea-water ingress through the blade seals, it was thought necessary to pressurize it with header tank supplied oil, and this required a further oil-way down the shaft—engineered by a double wall shaft arrangement. With these three sets of concentric tubes space is tight, and some elaborate support arrangements had to be provided to allow the hot air through. Starting again, we would probably simplify the installation and put the air down the 'A' bracket.

The design adopted has caused difficulties in shipyard assembly and setting to work. There are fifty-five sub-assemblies (excluding supply pipes and thrust blocks) in a two-shaft set, which have to be assembled in hydraulically clean conditions either in the ship or in dry dock. Follow-on shipbuilders learned the hard way, and it took time. Because the diametral space for the concentric OT tubes was so tight, the outer had complicated split-muff couplings. Keeping backlash out of these couplings was difficult. The inner tubes were screwed together and, because of the particular alloy used, the threads tended to cold weld during tightening. It was difficult to make the outer-hub pressurizing tube sleeve oil and air tight at its butt joints due to the problem of maintaining the very close tolerances required. When the joints leak the tubes must be pulled—an expensive and time consuming task. However the 64 official modifications noted earlier have overcome these problems, and now, with shipyards well up the learning curve, the assembly goes together on schedule.

One of the consequences of the spindle torque mal-prediction was, of course, that the hub gear was much more robust than it need have been. Not surprisingly very little trouble is experienced with it or with the blade attachment arrangements. On the other hand mechanical pitch-locking arrangements have given trouble and hydraulic pitch locking is very much to be preferred.

H.M.S. 'Invincible'

The foregoing CPP problems and their reasons were, of course, not known in 1968 when it was necessary to determine the mode of reversing to be adopted for H.M.S. *Invincible.* In this ship, however, constraints of space did not apply and, as over 40 MW per shaft from two Olympus engines was required, there was doubt whether a successful CPP hub of such size could be produced by extrapolation from current practice. There was thus a great incentive to opt for reversing gearboxes and even greater incentive to make sure we had a shore test rig to avoid first-of-class problems. Fortunately for this class there was time and thus was born the most powerful triple-reduction reversing gearbox in the world and the shore test facility at Ansty into which to put it.

This policy has been amply vindicated, for, whilst problems were encountered during shore trials, they were all overcome and *Invincible* went to sea without any fault ascribable to the design principle or its execution. Minor troubles there have been, but nearly all associated with quality control rather than design. The much publicized problem that she had with one of her hydraulic couplings on voyage to the Falklands (necessitating a change on passage) was in this category.

To sum up the CPP reversing problems of gas turbines, the R.N. chose to make a bed of nails to lie on, and we are getting used to the discomfort. Once properly assembled and flushed the system works well with reliability and precision. It did not, on any occasion, let us down in any ship deployed this year to the South Atlantic. A much simpler CPP design would, however, have been possible and would have saved a deal of money and heartache.

Controls and Surveillance

The 1960s brought the need to steam in action with unmanned machinery spaces to withstand nuclear, biological, and chemical attack. This led to secondary remote and automatic control exercised from central control rooms. With the advent of the TRIBAL Class, it became normal operating practice. The controls, as with the GMD destroyers, were pneumatic servo-manual for all but the boiler, which had automatic combustion—again with pneumatic logic. When changing over and engaging engines, the system was not foolproof and required a high level of operator expertise and awareness of the inherent dangers. At the time there was no driving objective to save overall crew numbers or provide more attractive working conditions—but these were welcome virtues.

With the introduction of gas turbines and CP propellers, coupled with a requirement for automated and 'bumpless' engine changeovers, our main controls objective was for good and consistent ship manoeuvring capability without overstressing the propulsion plant at any time. With the Type 42, and thus all the others, control was to be by single-lever operation from full ahead to full astern and the operator was to be divorced from any concern regarding over-torqueing, or over- or under-speeding of any drive component in the chain.

With such a stringent specification, it was clear that the pneumatic semi-automatic technology of the GMDs was no longer adequate and an electronic system was needed. Because the new machinery was to be widely dispersed, and also because the technology was available from current aircraft practice, a frequency analogue electronic control system was chosen, this being preferred because signal quality was less affected by transmission path length than other solutions. Hawker Siddeley Dynamics Engineering (HSDE) was chosen as the prime contractor as they had expertise stemming from helicopter control practice which had subsequently been developed for industrial gas turbine application.

A serious constraint on our controls development programme was the lack of time in the early 1970s to build a shore test main propulsion facility and run it before the first-of-class controls hardware design was finalized. This led to a good deal of 'play safe' engineering, which is still with us today. The modular control system was intended to simplify maintenance through employing a small number of main module variants adapted for discrete duty by some peripheral 'mini-modules', these all being individually tailored to their task. The main modules, containing a number of PCBs and cards, are 6-inch cubes and the mini-modules about one third of that size. Seven control modules, two surveillance modules, and seventeen different mini-modules were designed. In practice this led to 150 modules and mini-modules and initial unreliability. It led to a great deal of trouble with *Amazon* on her sea trials. Refining the hardware design before the trials was impossible, and the ship bore the brunt of all the de-bugging. With such a novel concept, this was to be expected, but a lot of valuable lessons were learnt, and not only by the British.

Mundane problems like a very high incidence of lamp failures on the consoles and stray earths were particularly annoying and required tedious modification work. The large one-piece welded construction of the consoles necessitated their installation at a very early stage in construction and caused cleanliness, upkeep, and modification implementation problems during the build process. These in turn caused unreliability. In all some 881 design changes, large and small, were needed to get the system to an acceptable 'MOD State Zero'.

Simulation

A vitally important aspect of our controls development programme from the beginning has been computer modelling of the machinery and control system dynamic responses. This has been handled by YARD Ltd. who were responsible for working up the detailed feasibility of the all-gas turbine concept as the Ministry's agents. Because of the complexity of the transient responses involving the variables of gas turbine speed, power, propeller-pitch and ship-dynamic behaviour, a hybrid computer system was chosen. Of all the exercises that we have undertaken in the change from steam to gas, this response modelling can be judged as one of the outstanding successes. From the outset, there was close correlation between simulated and designed performance in comparison with achieved sea trails. An early comparison set of traces, taken during *Sheffield*'s sea trials, is shown in FIG. 2.

Due to the way in which the COGOG machinery was developed contractually, all simulation work was done for the Type 42 Ministry-sponsored design and not for the Vosper-design AMAZON Class. During *Amazon*'s sea trials, however, the Olympus behaved differently, with the gas generator stalling

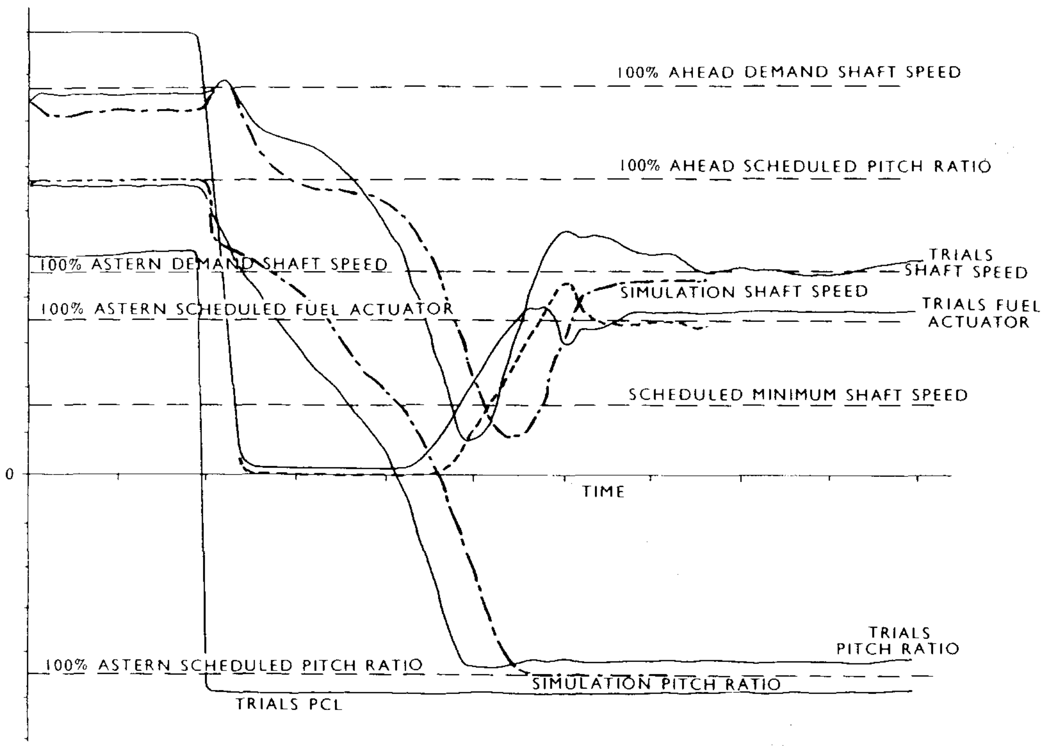


FIG. 2—COMPARISON OF H.M.S. 'SHEFFIELD' ACTUAL TRIALS RESPONSE OF CPP SYSTEM WITH MODEL PREDICTION

during manoeuvres. This, together with the significant differences in performance achieved in terms of ship response, made initial correlation and analysis of the results against the model of little help. Thus, when it was clear that substantial adjustments had to be made to the pitch-rate and other programmes, a new 'tailored' model was built virtually overnight to test our possible alterations to the control system during the sea trials. Had there been a shore-test facility for the control system, such urgent modifications could have been carried out there and tested before committing the ship. Nevertheless, the simulation computer played a vital role in achieving the ultimate success of *Amazon's* sea trials, and contributed similarly to the outstanding success of *Sheffield's* sea trials a year later. Even so, some of the adjustments ex-*Amazon* did not suit the deeper displacement and, on *Sheffield's* début, severe shaft underspeed during transients became a problem. Again, swift resort to the model saved the day.

With more time to engineer the system for *Invincible*, opportunity was taken to test a complete shaft set of controls in the shore-test facility at Ansty, and this policy paid off handsomely on sea trials. Although there was no shore-test facility for the BROADSWORD (Type 22) Class, a prototype set of controls was provided in advance of the ship and this also proved its worth for the first-of-class trials.

Machinery Controls Success and Developments

Since then the record of all ships has been very good, and the system has proved accurate and reliable, albeit at some cost. The design for upkeep is at the level of module and mini-module with no onboard facility to repair and retest these sub-assemblies, and they have to be returned to shore for refurbishment. Support is thus dependent on the availability on board of the correct modules to the correct modification state to suit the individual ship. This takes careful management, and in the early days caused some concern. The situation has now eased considerably with the module failure rate dropping to below four per operational ship-year. We entered the South Atlantic operation with twenty ship-fitted systems in the Fleet. They kept going and the logistics kept up. There were no problems.

One particular design handicap has been lack of flexibility in the concept—each new class has required much re-engineering of the hardware, and we are going through a similar phase now with adoption of SM1A gas turbines in later Type 22 frigates. Again, this is easy to say in retrospect when an electronic system, designed in the late 60s for a specific purpose, has been continued into the mid 80s for substantially new-design ships.

A lesson we have learnt in all this is that, like other systems, the development of gas turbine propulsion controls cannot wait upon specific ship projects. The timescales for controls development are long and need to be well on the way by the time a ship design is crystallizing. On each occasion that a change has been required recently to the machinery fit to Type 42s and 22s we have not been able to go to a suitably-developed system proved on a shore-test facility in advance. It has been a question of adapting what we already have. In a sense, over the last few years, it has been a bit like the CPP system, needing a new look but being defeated by project and short-term financial considerations, much to the frustration of both manufacturer and the Navy.

Real obsolescence of our controls systems has not yet arrived and with relatively minor changes to the engineering of modules the analogue style can be kept going for many years yet. For the last ships of the Type 22 Class, however, opportunity is being taken to fit a system re-arranged in racks rather than modules to make it both cheaper and simpler for fault diagnosis. This re-arrangement has been engineered for easy back-fitting to earlier ships if obsolescence does become a problem.

It was realized some years ago that there would be considerable advantages in changing to a digitally-based system with its own software programme substantially developed in isolation, and de-coupled as far as possible from ever-changing and improving digital hardware. This we have achieved by an exercise in writing programmes in a high-level language centred round Mascot and Coral. This software is specifically designed for portability and easy maintenance over along in-service life. It is being developed and tested in a digital-controls evaluation facility and we look to profit in flexibility, cheapness, ease of modification, and upkeep.

Diagnosis and Training

A further lesson we have learned during this change from steam to gas in the controls area is not to skimp on the provision for onboard fault diagnosis and crew training. The early fault diagnosis systems were quite inadequate and have been replaced in all ships with steadily improving equipment, the latest being BITE (Built-in Test Equipment) allowing performance checks when the system is off-line. It will locate faults down to module and mini-module level—thence to be rectified by module exchange. There is still room for further development as high diagnostic skills are still required at times.

For crew training it was decided very early on that a simulation control panel had to be provided ashore in advance of the first ship going to sea. This was achieved just a few months before *Amazon* first went to sea, and has been an unqualified success. This facility, together with the very comprehensive machinery interlocks provided on board and the operational success of the single-lever control concept, has ensured that with the full system in use the propulsion plant has never been damaged by operator error. For emergency use, a hand control is provided in all COGOG ships, inevitably by-passing some of the interlocks, so crew training in this mode is important.

For digital systems, and following the trend to move training from shore to sea, it is clear that a simulation model will need to be built into the seagoing control panel that will enable fault correction training and operator breakdown drills to be carried out with the ship at sea. How best to achieve this for the new Type 23 frigate is presently exercising our minds.

The introduction of automatic and remote control during the '60s was accompanied by a miscellany of primary and secondary surveillance equipments, mostly direct mechanical and pneumatic analogue within the technology of the day. We have seen that a strong motivating force in the change from steam to gas was saving in personnel, and the development of surveillance aids offered the maximum potential for achieving those savings. Much effort was devoted to providing facilities in the ship control centre (SCC) to allow completely unmanned machinery spaces. Although this has been a fair success, more could be done to develop the design of the SCC and the detail engineering of the primary sensors, actuators, and transmitters. These latter components were not procured to the same order of specification excellence as the gas turbines, and such things as fuel level transmitters, whilst not a ship stopper, can be frustrating when unreliable. We now have a rolling programme of primary and secondary surveillance system (PASS) and equipment development, again linked to the evaluation facility. We believe that this will enable us to engineer whole ship machinery control system and data-logging automation to match future crew numbers in the most reliable robust and up-to-date manner possible.

Auxiliary Energy

With steam propulsion plant, the provision of auxiliary energy presents few problems, and no multiple options—electrical power generation, fresh-water distillation, and hotel services all being best provided by steam in some form. Take away steam from main propulsion, add ever-increasing concern for economy, and a Pandora's box of options opens up. In a warship, these considerations cover about one third of the total energy consumption.

As with most design solutions, the choice is swayed by expediency, economy, and cost on the one hand, and simplicity and battle-worthiness on the other. Whatever other arguments might be deployed, for action damage considerations the R.N. has favoured those solutions that do not involve interdependence between one functional fluid system and another.

The prime decision required on the adoption of the GT policy was the method of electrical power generation. Since the war until the mid '60s there had been a major growth in power requirements in ships that at times had led to an awkward lack of installed capacity. This growth was predicted to continue, and all were determined to provide very ample initial capacity to avoid through-life shortfall in the new classes. Thus 1-MW generating units were adopted for the Type 42 Class with 100 per cent. redundancy in the system.

The choice lay between a high-efficiency complex-cycle gas turbine, a simple-cycle gas turbine plus waste-heat recovery, and high-speed diesel engines. The R.N. experience with the first two categories had been unfortunate. The twin-spool Allens gas turbo-alternator (GTA) fitted to the Type 81 frigates had suffered throughout its life from lack of initial development funding at the prototype stage, and consequent reliability problems had been built into production. This gave it a poor reputation that the concept did not deserve. Similarly, the Centrax gas turbine/waste-heat boiler trials unit in *Exmouth* suffered from lack of development funding and poor installation and again earned a poor reputation that was not representative of what could have been achieved.

Even so there are intrinsic problems with waste-heat boilers attached to gas turbines, particularly if the boiler cannot be run dry. Without a main-steam system to provide smoothing, auxiliary-steam demand is very cyclic in a warship, particularly where steam is used for distillation—this latter accounting for over 50 per cent. of the peak demand. Off-peak hotel-services demand is virtually nil, whereas electrical demand is much more constant. These disparities lead to poor matching in the combined auxiliary energy unit. Faults, contamination, and damage within the auxiliary-steam system, of low operational significance intrinsically, can have devastating import if they cause the GTA to shut down with consequent loss of power. Other navies using complex GTA/waste-heat steam system have suffered such problems.

A clinching argument in the choice of diesel generation was the lack of commercial GTA equipments in the one MW class. From the point of view of economy this choice could not be faulted, but it introduced other problems like hull noise and high maintenance.

Waste-heat recovery from diesel-jacket water was considered but again the cyclic nature of the demand, the increased complexity, and size all argued against its use in a surface warship. (It is used widely in R.N. survey vessels). A desalination method that might have been favoured for its efficiency utilizing diesel jacket water for pre-heat was by vapour compression; but R.N. experience with this (predominantly in Type 41/61 diesel frigates with electrical pre-heat) had not been good. Desalination using the standard steam-heated flash evaporators was therefore selected. Conversion of this distilling machinery to hot-water jacket heating was discussed, but discounted when it was found that electrical boost would be required under certain auxiliary-load conditions. Thus, although there were strong protagonists for an all-electric/waste-heat solution the time was not yet ripe for its introduction.

The consequences of the adoption of this final auxiliary energy policy on mission reliability have heavy dependence on the reliability of the diesel engines fitted and the auxiliary boilers used to supply steam for distillation.

Diesel Generators

The standard diesel engine chosen for the task was the same as that then being fitted by British Rail—the Ventura. It was expected that, because of the numbers fitted and cumulative running hours achieved by B.R., the R.N. would profit in the same way as it was to profit from similar considerations with gas turbines derived from aircraft. The change from steam to gas thus relied for its ultimate success on the excellence of this engine.

From the outset, the R.N. Ventura variant turned out to be less than perfect, and it has been subject to a long modification programme to eradicate inherent design weaknesses and manufacturing problems. Up till 1967 diesel generators in surface steam ships had been very much standby and harbour machinery used perhaps no more than 200 hours per year. Now they became the backbone of the main armament, to be on line all the time, with a required reliability much higher than before and running hours an order of magnitude greater. This requirement they initially did not achieve. Over 250 units in service later, with up to 150 modifications on each, has given us deep experience of the machine, and a current serviceability record that is satisfactory. The cost in both human and cash terms has been high. A big problem has been the deliberate over provision of generating capacity which has meant that where two diesels are run for operational safety (and this is the norm) they often run lightly loaded, and this the Ventura does not like any more than any other highly-rated diesel. A further problem is that the engine requires meticulous husbandry to achieve smooth and reliable running. These high standards were initially difficult to achieve in service because it took some time to improve the uniformed and civilian skill levels and material back-up to support the step change in running hours.

Steam Generation

Only slightly less annoying have been the problems with the auxiliary boilers. The model chosen was the Stone-Vapour Type 4740 with a capacity of 4500 lb/h at a pressure of 6·9 bar. This was already fitted as a harbour steam generator in LEANDER Class frigates and was in general use in British Rail, where 1000 or more were fitted (and many more in railways worldwide). In the LEANDER Class, it was little used as ships usually received shore steam in harbour, and was thus in the 'Cinderella' category claiming less than the best attention.

But in the Type 21s and 42s the ships' supply of fresh water and all the hotel services were critically dependent on it, and both the machine and the people who ran and supported it were found wanting. The machine itself suffered from a basic limitation of a small turn-down ratio (4 : 1) in face of a somewhat larger fluctuation in demand, and the ship's staff who ran it were not familiar with it. Now after a steady process of design modification and education it works well. The early boilers are being converted to a 10 : 1 turn-down to match easily the widest load fluctuations.

A post-design analysis was conducted some years ago on the Stone-Vapour boilers and it was concluded that all the problems then extant were in themselves trivial and, taken singly, of little significance, stemming variously from poor detailed engineering, poor support documentation, or operator ignorance. Taken together, however, they posed a major problem. This particular equipment is only emphasized because it is typical of the theme of this article—that the success of the overall concept has been so dependent on the excellence or otherwise of the detail design and execution of the auxiliary systems.

For *Invincible*, the same auxiliary energy arguments were applied and the same solutions emerged, this time with 1·5-MW Valenta diesels and larger (6500 lb/h) Stone-Vapour Type 6969 boilers. On the face of it, the boilers were too small, with five fitted, but again it was a question of taking something we knew from current practice, accepting the problems, rather than start again. Warnings were given at the time that, unless the reliability of the Valenta diesel was substantially better than the Ventura, overall availability would be jeopardized. Fortunately the requirement has been met and the Valenta diesel has turned out to be a great success.

Reverse Osmosis

For many years, the Navy has been seeking to limit the auxiliary energy absorbed in making fresh water—800 kW of low-grade heat being a typical demand. The front runner to replace steam-driven plant has been desalination by the reverse osmosis (RO) principle. The energy saving attractions of RO can be seen at a glance from FIG. 3 and this gives us the incentive to persevere. The other incentive is that it unlocks the door to all-electric auxiliary energy solutions, thus finally making the break from steam in gas-turbine ships. Machines of this type have been about for many years, and indeed were considered for the Type 42 in 1969 but then, and subsequently, were discarded on reliability and maintainability grounds. The membranes were too delicate for naval use and their lives too short. Further problems come with the material engineering of the high-pressure (60 bar) sea-water feed pumps, and the need to filter the sea-water feed to 10 micron level—difficult in estuarine waters.

However, development was continued and by April 1982 we had reached the satisfactory stage of testing a prototype for the new conventional submarine T2400 and writing it in as a tentative first choice for the Type 23 frigate. The South Atlantic operation then gave the cause of RO, and its use in the RN, a tremendous boost when a large number of commercial sets were purchased for the requisitioned merchant fleet to augment their drinking-water facilities. The message that is still coming back from this exercise is that they performed well but close attention to the sea-water pre-filter system is needed for success.

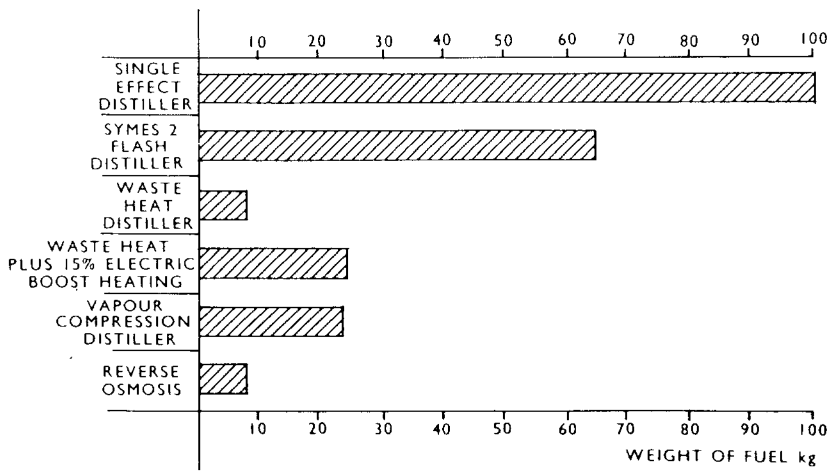


FIG. 3—WEIGHT OF FUEL TO MAKE ONE TONNE OF WATER

The elimination of steam in gas-turbine ships is not all advantage, particularly for space heating and fuel pre-heating. In arctic situations both demand large quantities of low-grade heat which, if electric, is expensive to supply and control. A very careful balance of first and through-life cost has to be made to see whether such options as diesel jacket water-heated hot pressurized water systems—similar to ordinary domestic central heating—might be better. Again, these throughts are exercising our minds for the new Type 23 frigate.

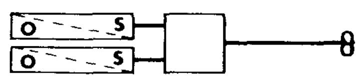
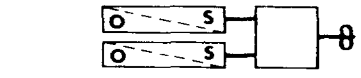
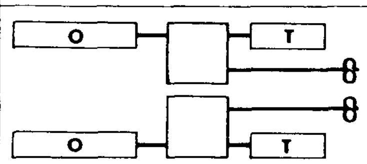
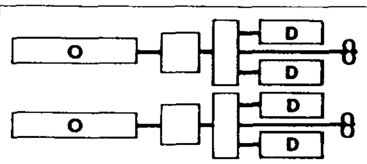
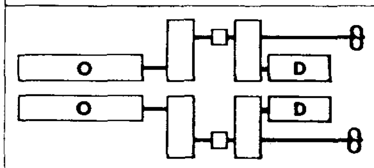
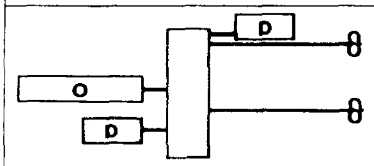
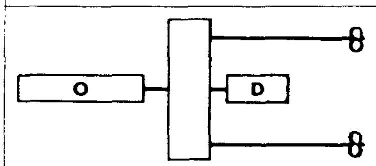
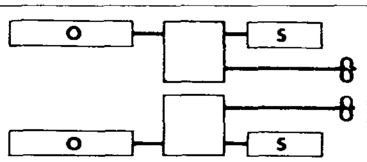
Fuel and Economy

The availability and economic use of fuel were central issues in our change from steam to gas. The fact that early gas turbines were profligate in this regard precluded their use alone in major warships until a satisfactory cruise unit had been developed. However, the change from naval furnace fuel oil (FFO)—itself a blend of residual and distillate fuel—to the distillate diesel oil (F-76) was a product of earlier years. We made this change in the steam era in order to give longer life to our boilers on their gas side and make maintenance, cleaning, and logistic supply simpler. Worldwide, there is now a rapidly reducing capacity and inclination to produce the naval FFO grade in favour of the 'heavier residuals' and diesel oils. A future naval steam boiler, burning 'predicted future grade residuals', would not be an attractive military option for a small ship even allowing for improvements in the state-of-the-art of steam systems.

The whole character of our gas-turbine solution depended on a 0–100 per cent. power/fuel-consumption curve that would stand comparison with the best current steam systems, then taken as LEANDER Class performance, including comparable performance at an economical cruise speed that was set higher for gas-turbine ships than for LEANDERS. In practice, it has so turned out. Over a full operational year the gas-turbine ships have proved more economical than the steam-driven escorts. The Type 21 frigates have been particularly noteworthy as the miles travelled have been at a higher average speed than steam frigates, and for the Type 42s the edge in economy has been maintained with a larger ship.

One of the contributory factors to this success has been the use of all-diesel power generation in the gas-turbine ships, and this economy makes the diesel attractive as a cruise engine. We chose the Tyne for cruise propulsion purposes in 1967 but, given the availability of suitable diesels in the 4-MW plus power range, there may be a move away from all-gas to combinations of the two for the future. Against this there is a very strong case in larger escorts for a multiple set of identical mid power-range second-generation gas turbines, where only one is needed to give the cruise speed required. Such an engine is the SM1A and it is on this at 12·75MW that the Navy is centring its future large 'frigate' strategy. With this economical engine in multiples or in combination with modern fuel-efficient diesels, we are now well into the phase of diminishing fuel saving returns from consideration of prime movers and auxiliary-energy systems alone. Any further complication in pursuit of economy, at least for the smaller ship, has scant justification. FIG. 4 shows a chart of engine combinations that are now either in service or planned in the many navies using British gas turbines.

In any consideration of the type of fuel used and of gas turbines versus steam, it is as well to remind ourselves where the Navy stands in relation to oil-fuel consumption in the rest of the U.K. At 3 per cent., the MOD is the third largest national user after CEGB (at 10 per cent.) and British Steel (at 4 per cent.). Of the MOD total, the Navy uses one third approximately. At 1 per cent. of the national consumption therefore, we are not in any position to dictate special requirements to the industry, but must be ever ready to exploit commercial developments funded on a national scale. Land and air transport are prime users of distillate hydrocarbon fuel, and it is believed that this transport quality premium fuel will be nationally available through commercial pressure all through the long lives of our next generation of ships, and eventually from other sources such as coal synthesis. We therefore see no great pressure to change the chosen propulsion modes for smaller warships away from gas-turbine and diesel combinations. We believe that burning commercially available residual fuels (at half the future cost of diesel oil) for the sake of price economy is not a reasonable military option. The R.N. is faced with, and must accept, fuel costs which have risen from 1 per cent. of total through-life ship costs in 1963, through 3 per cent. in 1973, 15 per cent. in 1980 to perhaps 25 per cent. and beyond in 2020.

PROPELLERS	ARRANGEMENT	ENGINES	MODE	CLASS
2		4 Olympus	COGAG	Aircraft Carrier HMS *Invincible*
		4 SM 1A	COGAG	(proposed) Sea Control Ship 3500 t Destroyer
2		2 Olympus ✱ 2 Tyne	COGOG	Type 42 Destroyer HMS *Sheffield* Type 21 Frigate HMS *Amazon* Type 22 Frigate ✱ HMS *Broadsword* HrMs *Kortenaer* Japanese Navy Destroyer
2		2 Olympus 4 Diesels	CODOG	Brazilian Navy Mark 10 Frigate *Niteroi*
		2 Olympus 2 Diesels	CODOG	French Navy Corvette *Georges Leygues* Libyan Navy Mark 7 Frigate *Dat Assawari* Imperial Iranian Navy Mark 5 Frigate *Saam* Nigerian Training Frigate
		1 Olympus 2 Diesels	CODOG	Belgian Navy E71 Corvette *West Diep* Yugoslavian Training Ship Dutch/Indonesian Corvette
		1 Olympus 1 Diesel	CODOG	Royal Thai Navy Frigate *Makut Rajakumarn* Royal Malaysian Navy Frigate *Rahmat*
2		2 Olympus 2 SM 1A	COGAG	Japanese Navy Destroyer

✱ OLYMPUS in some later Type 22's being replaced by SMIA

FIG. 4—R.N. TYPE GAS-TURBINE MAIN PROPULSION APPLICATIONS FOR FRIGATES AND ABOVE PRESENTLY IN SERVICE OR PROPOSED

Fuel Treatment

The gas turbine brought its own problems of diesel fuel handling on board ship. Firstly, water. In itself, pure water is no problem to the gas turbine. But fuel at sea nearly always contains water, and salty water at that. In search of economy, gas-turbine maximum temperatures are pushed to a metallurgical limit where life is critically dependent on contaminants, and a real cause for concern is sodium in the fuel. Hence we are critically dependent on the efficiency of the water separation machinery provided to us and the situation is not helped by salt-water displaced fuel tanks.

Secondly, fuel purity. The current generation of marine gas turbines uses a hydraulic fuel-control system with the fuel as the actuating fluid. There are fine clearances in this equipment, which require a maximum particle size of 5 microns in the fuel supply to the engines. To a certain extent, filtration to this level is a by-product of the water-removal process, and a change in engine design to avoid using fuel in fine clearance machinery would not necessarily alter the amount of fuel clean-up plant required to be carried.

Critical to our ability to achieve clean fuel to these standards when operating in cold areas is the cloud point of the diesel fuel. At present the figure stands at -1°C, but we see a commercial trend to force it up as far as 4°C. This would bring problems which can only be overcome either by installing tank and system heating or by continuing to control, at extra expense, the cloud point of military fuel by specification.

In retrospect, it is clear that we needed a very thorough continuous fuel-treatment process capable of taking the full-power through-put without expending filtration consumables. Using a combination of fuel centrifuges and coalescer elements this has only been completely achieved in the INVINCIBLE Class and the later escorts. In the particular case of the INVINCIBLE Class however, fuel filtration problems have been exacerbated by uncoated fuel storage tanks which give rise to excessively fine rust particles in the fuel. These tend to by-pass the centrifuges to an unacceptable degree, and lead to high coalescer element usage.

During the last fifteen years, the problem of biological mould growth in diesel fuel has been increasing. Clearly this is not due to the advent of gas turbines alone, other than the fact that they have much increased the volume of diesel oil used, stored, transported, and shared between navies round the world, together with the wider use of displaced-fuel tanks in escorts for stability reasons. Fuel mould has probably always been with us, but the above factors have made it easier to grow and to spread. Fortunately the detritus products are transfer pumpable, and provided full flow centrifuges are installed before the ready-use tanks and water-separation equipment, the gas turbines suffer no ill effects. The possibility of pasteurizing exists but has so far not been used on board ship. Infection control in shore stocks is, however, a major activity for our logistic department. The latter was well tested during the South Atlantic operation, and more contaminated fuel than may have been desirable appeared in the Task Force.

In addition, for the future, we will need to improve our fuel treatment facilities on board in face of reducing commercial standards particularly regarding wax content.

To sum up as far as fuel economy is concerned, in ships under 10 000 tonnes we feel our propulsion and auxiliary energy strategies outlined above give us the best options available, without undue complication, well into the twenty-first century. Above 10 000 tonnes more complicated systems start to become viable, as demonstrated by a U.S.N. programme, where the waste heat from LM2500 gas turbines (of similar fuel consumption performance to the SM1A) is passed out to a steam-raising boiler coupled to a propulsion steam-turbine boost system. Near diesel economy is claimed, and we watch developments with interest. Given that only 50 per cent. of the Navy's fuel is actually burnt in warships, (25 per cent. being used ashore, 20 per cent. in fleet auxiliaries, and 5 per cent. in aircraft), whilst every effort will be made to improve the economies of the gas turbines and diesels under discussion, much greater scope exists for economies in the other sections—such as investment in lagging of buildings and modernization of the fleet auxiliary tonnage.

Supporting the New Style

During the steam era, a refit policy of refurbishment of auxiliaries by exchanging them for previously refitted similar equipment had been growing in order to save time in dockyard hands and remove the criticality of dockyard factory loading. A primary objective of the change from steam to gas was to reduce onboard work and thus crew numbers, together with a general reduction in the level of craft skills needed for that on-board work. Thus, the policy of refit by replacement in dockyard hands was extended during operational time to upkeep-by-exchange of the major proportion of assemblies and sub-assemblies including the gas-generator ends of the main propulsion sets. It was envisaged that the remaining ship's company should be required to open up only a small proportion of the equipment for on-board refurbishment, and certainly not the gas generators.

This policy was vital to the general change objectives, but brought problems in its wake. It made the availability of the Fleet critically dependent on the availability of the right replacement sub-assembly at the right place and time. In terms of capital tied up in hardware it was, and still is, expensive. This expense, however, needs to be set against the cash and space savings accruing from the reduced manning standards.

After some ten years of working to this policy with considerable success, it is clear that there needs now to be some amendment to take account of that experience. A major factor is the high technical quality of the skilled ratings now on board. Because diagnostic management and operative skills required in the new propulsion style have remained high, the intellectual quality of those men has also remained high, and with this has remained their natural abilities to diagnose, strip, and repair faulty sub-assemblies. There is evident frustration that these skills are not being given outlet because the policy has not given them the special tools, instructions, and spare gear on board that would be necessary. It is also a waste of talent, and if we can use that talent to the advantage of lessening the criticality of the logistic chain, so much the better. There are also obvious spin-offs in the improvement in morale and job satisfaction that such relaxations will bring.

For the aero-derived gas turbines themselves, it was clear from the beginning that a more rigorous approach to support provisioning would have to be adopted than the somewhat *ad hoc* methods previously used at the beginning of a steam propulsion project. Just how rigorous we did not appreciate until late, and in the early days there were some shortfalls in spares availability. The initial predictions by the suppliers, based on aero-engine practice, did not read across to what actually happened in service to the marine variants. A prime factor has been our ability to return defective repairables (not only gas turbine items) quickly to the overhaul facility, turn them round there and get them out again. With initial under provision of gas-turbine change units, the situation tended to criticality.

Early fears that the gas-turbine policy would put the Navy at the mercy of one commercial engine overhaul facility led us to set up a second 'in house' at the R.N. Aircraft Yard, Fleetlands. This was a good strategic move but, with the welcome increase in life that continuous modification programmes have had on all our current engines, the workload at the

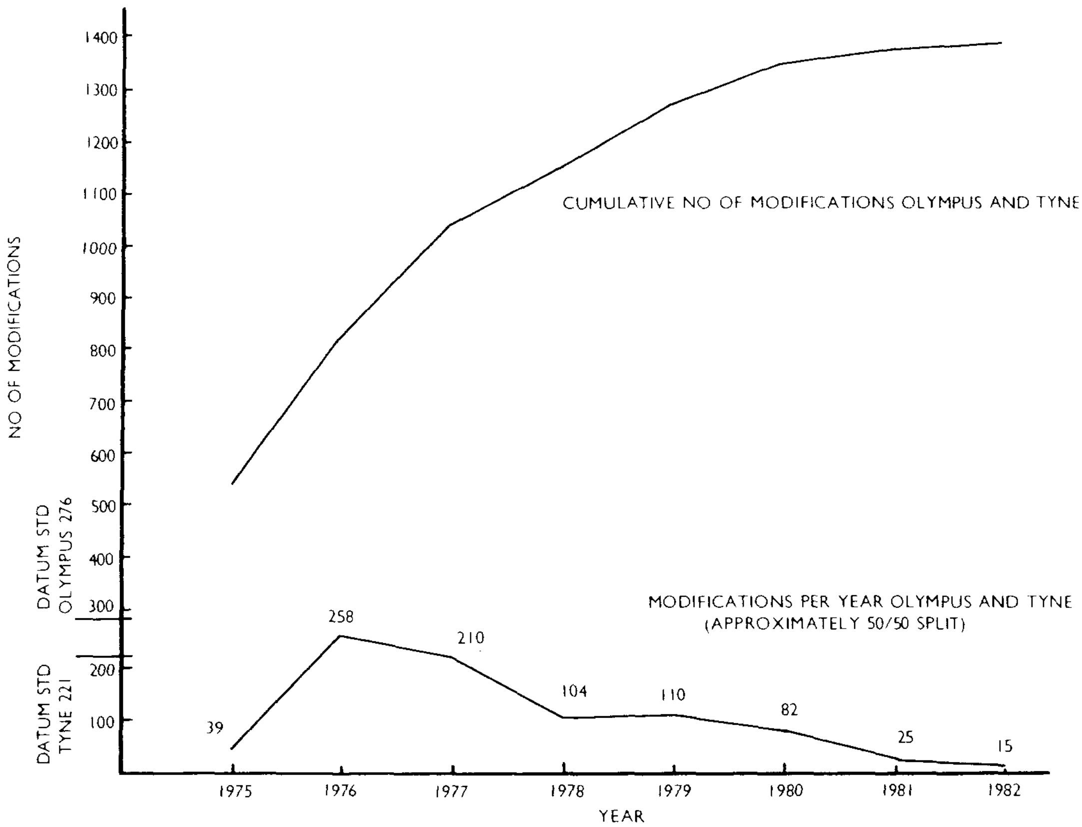


FIG. 5—OLYMPUS AND TYNE GAS-TURBINE MODIFICATION RATE

commercial facility has dropped to what may approach an uneconomical level even with the 'foreign users' workload.

Sixteen navies have fitted similar engines and, of these, there is a memorandum of understanding between the British, Netherlands, Belgian, and French Navies over the sharing of a joint pool of gas turbine change units and spare sub-assemblies. This is administered from Britain, and it is assisted by a computer model to predict usage, stocking, and re-ordering rates, and to control allocations.

In the context of the continuous modification programmes mentioned above, it is now quite clear that although naval marine engineers did understand in 1967 that they were buying into major prime-mover equipments that, unlike steam machinery, would need progressive modification to achieve the target overhaul lives, none of them really appreciated the scale of the activity. Had they asked an aero-engineer of the day he would quite naturally have said 'modification programmes go on for ever'—and so it has seemed to be. We were not well prepared for the consequences and had to take several hard looks at our procedures before we got them right. There was, and still is, a deal of work in checking for interchangeability spare stocks to match a roving population of change units, changing documentation, making sure everybody knows. FIG. 5 shows the extent of the problem in the early years, which was only diminished latterly through the Ministry's disinclination to approve and fund the manufacturer's more recent proposals. The flow of ideas remains high.

A great deal of initial study was put into ensuring that the gas generator change unit removal routes and exchange process equipments gave the easiest possible task to the team carrying out engine changes. It was very successful from the start, and few alterations have been needed. With the exception of the INVINCIBLE Class and the Tyne engines in the Type 21 frigates however, all engine changes are dependent on the availability of a fine lift control crane external to the ship. This has not proved a great handicap to date but clearly future designs will need to eliminate this dependancy.

The Future

We have learned a great deal about all-gas-turbine propulsion in the past ten years, and this knowledge is there to be exploited in the next generation. There is always an undercurrent of sentiment towards a return to steam for reasons that should now be clear from this paper. Equally, there are excellent reasons why we should continue with gas turbines in the vessels we plan to build, at least for the full-power requirement if not always for the cruise mode. They have been a great success.It will be a different matter in larger warships and for those, if we do not adopt nuclear power, then modern fossil-fired steam has something to offer. Bearing in mind the Navy's traditional reluctance to fit complicated interdependent-cycle machines, adopting large energy saving gas-turbine/steam-cycle systems in the medium term seems unlikely.

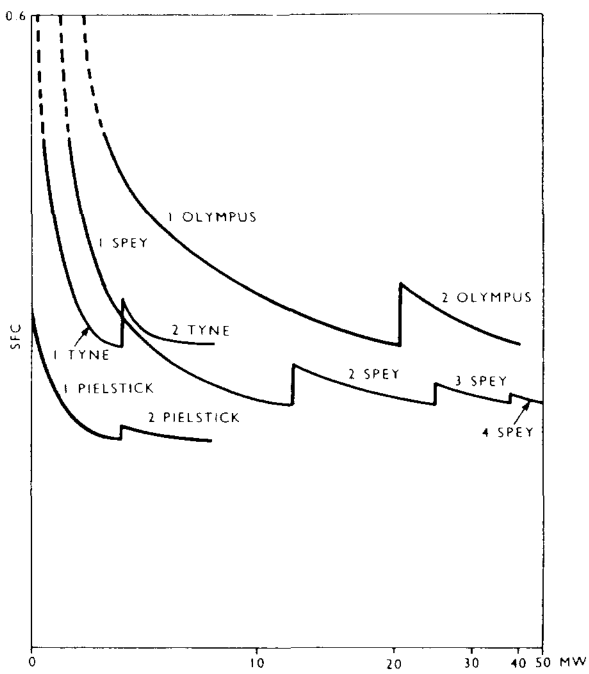


FIG. 6—COMPARATIVE SFC FOR VARIOUS ENGINE COMBINATIONS IN AN ESCORT OF APPROXIMATELY 4000 TONNES

The Navy at last has its intermediate-power gas turbine in the 'second generation' 12·75 MW SM1A engine. FIG. 6 shows how this engine might be employed in terms of specific fuel consumption in relation to the existing fleet escorts. It will be fitted in the seventh Type 22 now building and in others of this class later. It is the first choice for our new Type 23 frigate, where it will be fitted as an ahead-only boost unit in conjunction with diesel-electric for cruising and manoeuvring (CODLAG). This somewhat unusual combination has been proposed as a response to a Naval Staff requirement for prolonged slow operation and high top speed. Should we be required to build a new design fleet escort destroyer again then a four-SM1A fit with simplified reversing arrangements in the gearbox or propeller would be hard to beat. For steam to compete in terms of overall economy a 525°C–82 bar pressure system would be required which, while within the state-of-the-art technology, would still require substantial defence investment for which there could be little hope of commercial spin off. It would be a brave man that would commit such a solution to burn the quality of residuals likely to be commercially available in the twenty-first century purely for the sake of 10 per cent. through-life cost reduction, for to do so would be to ignore the problems which forced us away from the much purer semi-distillate FFO, now rapidly disappearing from commercial availability. The Steam lobby will argue that 10 per cent is a lot to be giving away and that a future new design naval boiler would cope with the residuals. In consideration of all these arguments, we keep our options open by letting out 'future surface steam-propulsion' study contacts for power ranges comparable to that provided by a four-SM1A fit.

On the support front, there may be a limited return to on-board and *in-situ* repair of sub-assemblies and emphasis in new design on self-help capability when it comes to changing main engines. Removal routes will be simplified, and we are already seeing the beginning of this with side ways removal of the SM1A change units from the module, avoiding disturbance of the intake ducting. The trend to reduce manpower will continue, and this will demand new initiatives in machinery control and surveillance design. The Falklands operation concentrated everybody's minds on swift turnround of repairables, and this improved logistic momentum will be sustained.

The future will hold just as many challenges for naval marine engineers as it has in the past. Some of the predictions made here will be wrong, but without prediction the engineer will not advance and advance we must. For those still around who stumble on this paper in the year 2020 it may make amusing reading. If the Navy is performing as well then as it is now we will have much for which to be thankful.

Disclaimer

The views expressed in this article are those of the authors. They do not necessarily reflect those of the Ministry of Defence or Industry.